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The National Ignition Facility: The World's Largest Laser

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The National Ignition Facility: The World's Largest Laser

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***Abstract.* The National Ignition Facility (NIF), currently under construction at the Lawrence Livermore National Laboratory, is a stadium-sized facility containing a 192-beam, 1.8-Megajoule, 500-Terawatt, ultraviolet laser system together with a 10-meter diameter target chamber with room for nearly 100 experimental diagnostics. When completed, NIF will be the world's largest and most energetic laser experimental system, providing an international center to study inertial confinement fusion and the physics of matter at extreme energy densities and pressures. NIF's 192 energetic laser beams will compress fusion targets to conditions required for thermonuclear burn, liberating more energy than required to initiate the fusion reactions. Other NIF experiments will allow the study of physical processes at temperatures approaching 10^8 K and 10^{11} Bars, conditions that exist naturally only in the interior of stars, planets and in nuclear weapons. NIF has now completed the first phases of its laser commissioning program. The first four beams of NIF have generated 106 kilojoules of infrared light, exceeding design requirements. Operation of single beams at the second harmonic (531 nm) and third harmonic (351 nm) at greater than 10 kilojoules have also exceeded the performance criteria. NIF's target experimental systems are being commissioned and experiments have begun. This paper provides a detailed look the NIF laser systems, laser and optical performance and results from recent laser commissioning shots, and plans for commissioning diagnostics for experiments on NIF.**

I. INTRODUCTION

The National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory (LLNL) will be a center to study inertial confinement fusion and the physics of extreme energy densities and pressures. The building housing the laser system was completed in September 2001 and construction of all 192 ultra-clean and precision aligned beam path enclosures was completed in September 2003. In late 2002 NIF began activating its first four laser beam lines and by July 2003 NIF had delivered world-record single laser energy performance in primary (1.06 micron infrared light), second, and third harmonic wavelengths. The first diagnostics capability has been installed and physics experiments have begun.

When completed in 2008, NIF will provide up to 192 energetic laser beams to compress deuterium-tritium fusion targets to conditions where they will ignite and experience thermonuclear burn, liberating more energy than is required to initiate the fusion reactions. NIF experiments will allow the study of physical processes at temperatures approaching 100 million K and 100 billion times atmospheric pressure. These conditions exist naturally only in the interior of stars and in nuclear weapons explosions [1-4].

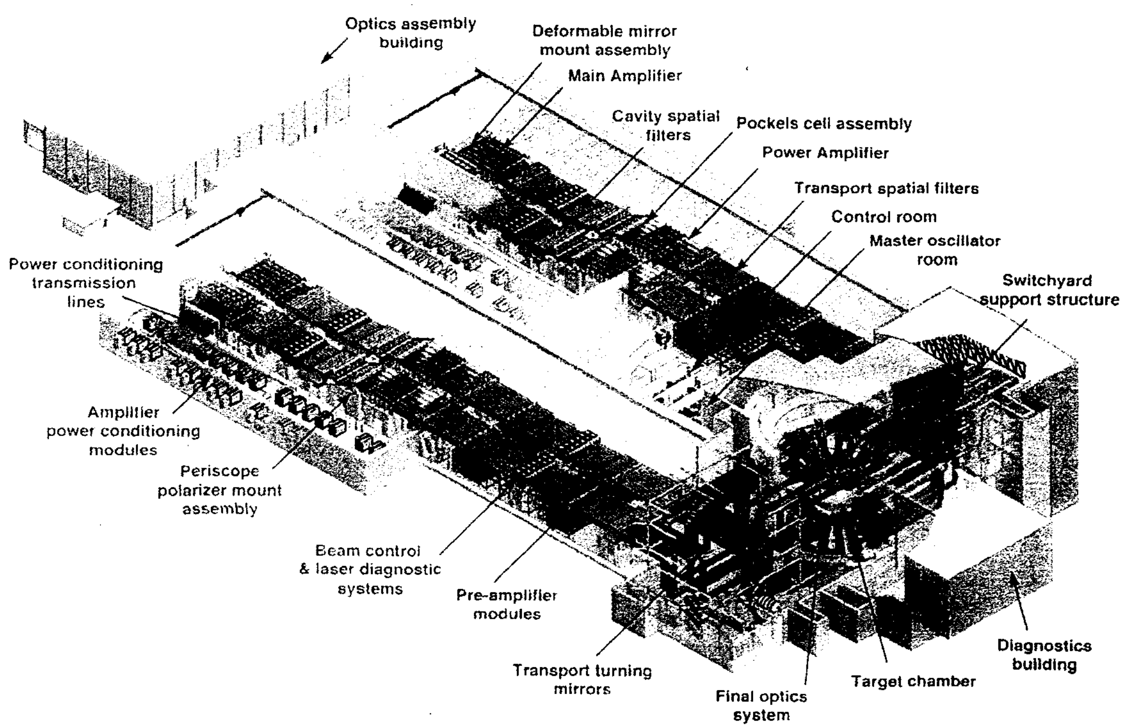

Fig. 1. Schematic view of the National Ignition Facility showing the main elements of the laser system. The 10-meter diameter target chamber sets the scale for the facility.

II. THE NIF LASER SYSTEM

The National Ignition Facility layout is shown in Figure 1. NIF consists of a number of sub-systems including amplifier power conditioning modules to drive large flashlamp arrays that power the neodymium-doped glass laser, the injection laser system consisting of the master oscillator and preamplifier modules, the main laser system along with its optical components, the switchyards, and the 10-meter diameter target chamber and its target experimental systems. The entire laser system, switchyards, and target area is housed in an environmentally controlled building. An integrated computer control system is located in the core of the facility to monitor, align, and operate the more than 60,000 control points required for NIF's operation. A 2,000 square meter cleanroom facility, the Optics Assembly Building, is located at one end of NIF for assembling and installing the precision optical and opto-mechanical components that make up the NIF laser system. On the opposite end of the facility the Diagnostics Building houses experimenters, a data acquisition system, and target preparation and storage areas.

The NIF laser system is comprised of 192 high-energy laser beams. For inertial confinement fusion studies the laser beams will produce a nominal 1.8 million joules (approximately 500 trillion watts of power for 3 nanoseconds) of ultraviolet laser energy onto a target. This is approximately 60 times the energy available in the Nova laser, which was operated at LLNL between 1983 and 1999, or the Omega Laser at the University of Rochester's Laboratory for Laser Energetics. NIF is capable of providing a range of beam energies and powers for experimental and diagnostic x-ray backlighter applications.

NIF's architecture and operation have been described in detail elsewhere [5,6]. NIF includes a single master oscillator with arbitrary waveform generation capability split into 48 pulses feeding a high-gain preamplifier system. Each preamplifier injects joule-level pulses into a "quad" of four beams in the main laser system. Each beam is approximately 40 cm x 40 cm in area. The main laser system consists of two stages of large flashlamp-pumped neodymium-doped glass amplifiers with multi-pass capability for both high gain and high energy extraction efficiency. Laser light is switched in and out of the main amplifier cavity using full aperture plasma-electrode Pockels cells and polarizers. Each laser beam utilizes a full-aperture adaptive optic deformable mirror to correct wavefront aberration. The total amplification factor for the 192-beam system is over 10^{15}. High energy laser beams are transported in quads through argon-filled beam tubes to final optics assemblies located on the target chamber. Final optics convert the laser light to the third harmonic, focus the light to target chamber center and provide diagnostic sampling and debris protection.

Figure 2 shows one of the 192 laser beams, detailing the key elements of a NIF beamline, called line-replaceable units.

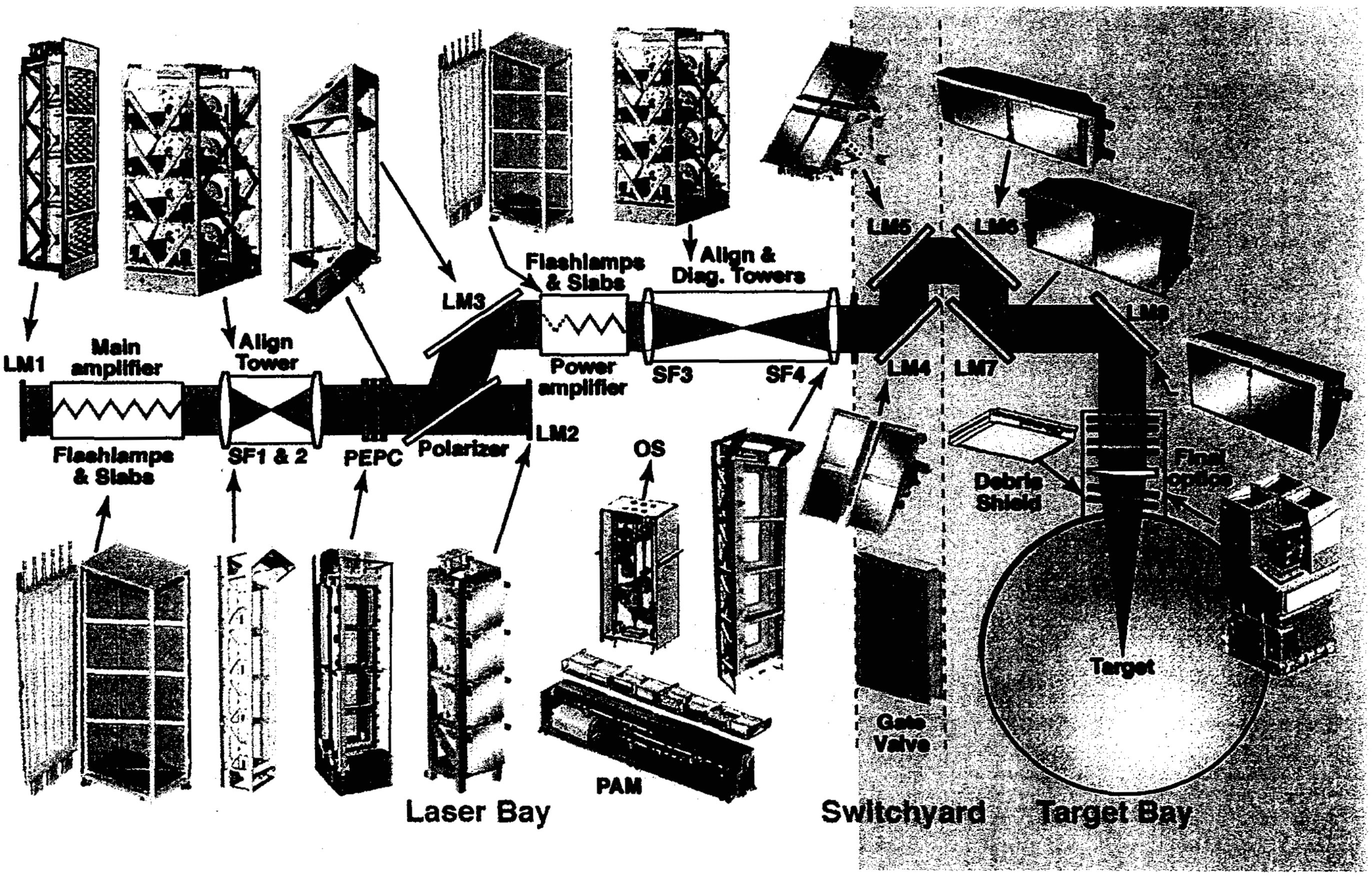

Fig. 2. Schematic representation of a NIF laser beam line showing the line-replaceable units in each line.

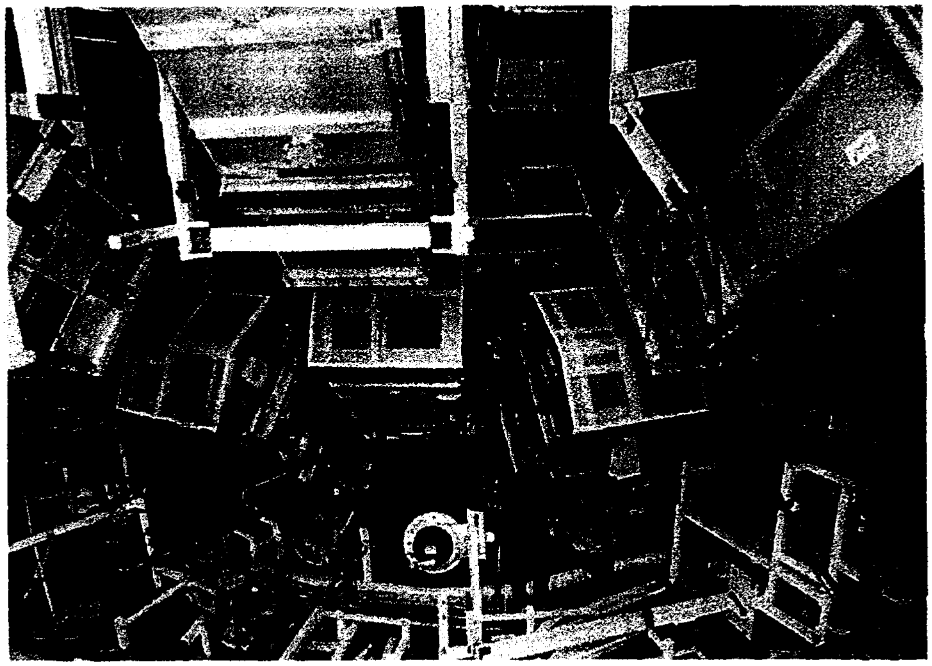

Fig. 3. Photograph of the target chamber upper hemisphere with quads of beam tubes being installed.

All major laser components are assembled in clean, prealigned modules called line-replaceable units or LRUs. These LRUs contain laser optics, mirrors, lenses, and hardware such as pinhole filter assemblies that are designed to be robotically installed into NIF's beampath infrastructure, while maintaining the high level of cleanliness required for proper laser operation. Autonomous guided vehicles carrying portable clean rooms position themselves underneath NIF's beampath enclosures and robotically insert LRUs into the beampath. The installation, integration, and commissioning of the beampath infrastructure at the required cleanliness levels has been successfully accomplished for the more than 120 LRUs required for NIF's first four laser beam lines.

NIF's 10-meter diameter target chamber includes a number of laser entry ports that allow quads of four laser beams to be focused to the center of the target chamber through a final optics assembly (FOA). The FOA is a precision optical assembly containing optics to provide a variety of spatial beam

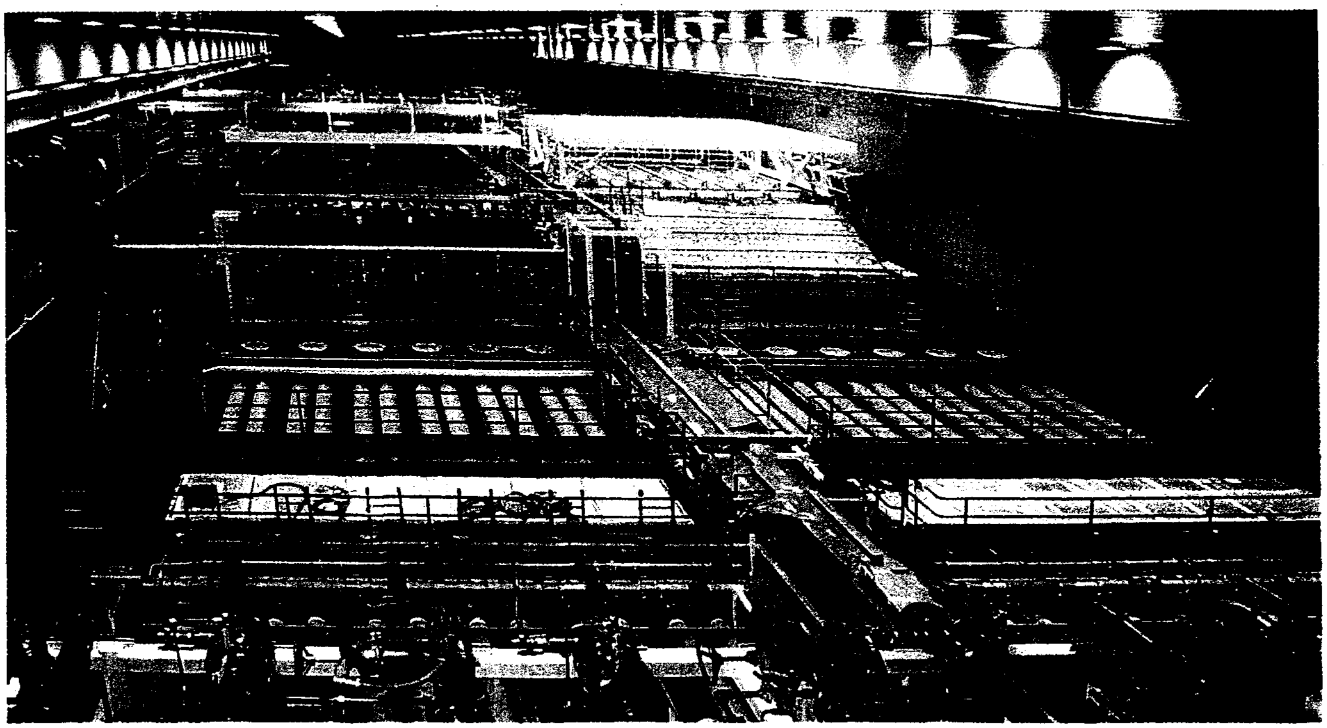

Fig. 4. Photograph of the completed beampath in Laser Bay 2

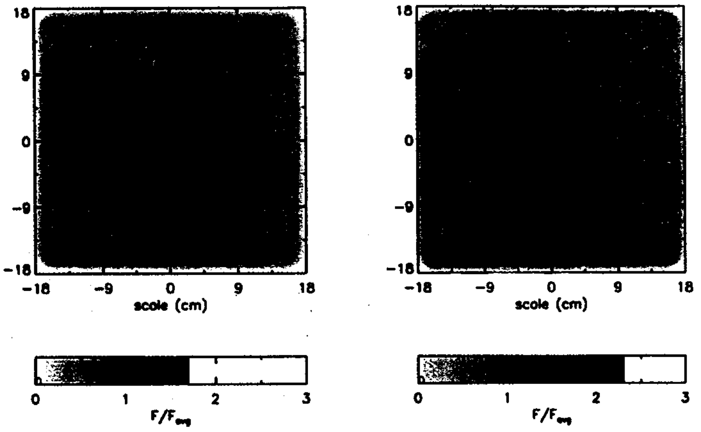

Fig. 5 Near field image of an 11.4 kJ 2ω and 10.4 kJ 3ω NIF beams showing excellent contrast uniformity.

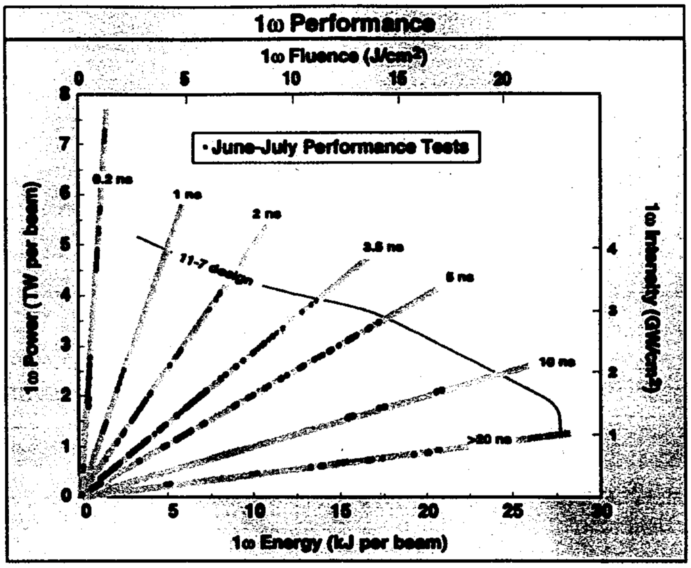

Fig. 6 1ω energy versus power is plotted here for a number of NIF performance shots. The plot also indicates the level where energy and power is limited by the available number of glass slabs in the main amplifier (11 slabs) and the power amplifier (7 slabs).

profiles on target, KDP and deuterated KDP plates to convert the infrared laser light into the ultraviolet, the final focus lens, debris shields and vacuum gate valve for each beam.

NIF uses over 7,500 large optics, including glass slabs, KDP crystals, mirrors, windows, lenses, polarizers, and diffraction gratings. There are over 26,000 smaller optics used in the Injection Laser System [7,8].

The NIF target chamber and final focusing system has been designed with maximum flexibility for experimental users with 120 diagnostic instrumentation and target insertion ports. During initial operation, NIF is configured to operate in the "indirect drive" configuration, which directs the laser beams into two cones in the upper and lower hemispheres of the target chamber. This configuration is optimized for illuminating the fusion capsule mounted inside cylindrical hohlraums using x-rays generated from the hot walls of the hohlraum to implode the capsule. NIF can also be configured in a "direct drive" arrangement of beams, by moving some quads of beams into a more symmetric arrangement of beams. Figure 3 shows a recent photograph of the upper half of the target chamber.

III. NIF Early Light

NIF construction began in May 1997 and nearly all 192 beampath enclosures are now in place and ready for optics installation. Figure 4 shows the beampath installed in Laser Bay 2. In October 2001 the first laser light from NIF's master oscillator was generated in the master oscillator room located in the central core of the NIF building. This master oscillator has demonstrated the required pulse shaping stability and accuracy for high contrast ignition pulses and other types of laser pulses that are of interest to NIF experimenters. In June 2002 the first preamplifier module was installed in the Laser Bay and routinely amplifies master oscillator pulses to the joule level.

First high energy 3ω laser light to the center of NIF's target chamber was achieved in January 2003 with approximately 1 kilojoule (kJ) of laser energy focused onto a simple foil target. The energetic x-rays emitted from this target were measured with an x-ray pinhole imaging system called the Static X-ray Imager (SXI) mounted on the target chamber. In April 2003 10.6 kJ of 3ω light was produced in four beams and directed to a target in the target chamber. Recently we have delivered 16 kJ of 3ω light in four beams to the target chamber for experiments.

A separate target chamber, known as the Precision Diagnostic System (PDS) is being used to fully characterize NIF's laser performance. Any one of the four activated NIF beams can be directed into the PDS using a special robotic mirror and transport system. Data from the PDS is being used to validate and enhance computer models used to predict laser performance. A series of laser energy and power performance campaigns have been carried out using PDS to characterize 1ω, 2ω, and 3ω performance. Figure 5 shows examples of high-energy 2ω and 3ω beams imaged in the near field using the PDS.

At this time NIF's highest 3ω single laser beam performance is 10.4 kJ, equivalent to 2 MJ for a fully activated NIF, exceeding the NIF energy point design of 1.8 MJ. The 10.4 kJ 3ω energy was achieved with 13.65 kJ 1ω drive in a 3.5 ns pulse. Also during this time a series of shots were conducted generating green or 2ω laser light with single beam energy up to 11.4 kJ in a 5 ns square pulse. This is equivalent to nearly 2.2 MJoule on target for 192 beams. In July 2003, 26.5 kJ of infrared light per beam was produced. This energy is 30% greater than the drive energy required for NIF. NIF has now demonstrated the highest energy 1ω, 2ω, and 3ω beamlines in the world.

High power shot campaigns have also been completed with drive power reaching 7 terawatts or about 5 gigawatts/cm^2. Figure 6 details energy and power achieved on a number of 1ω shots conducted through July 2003.

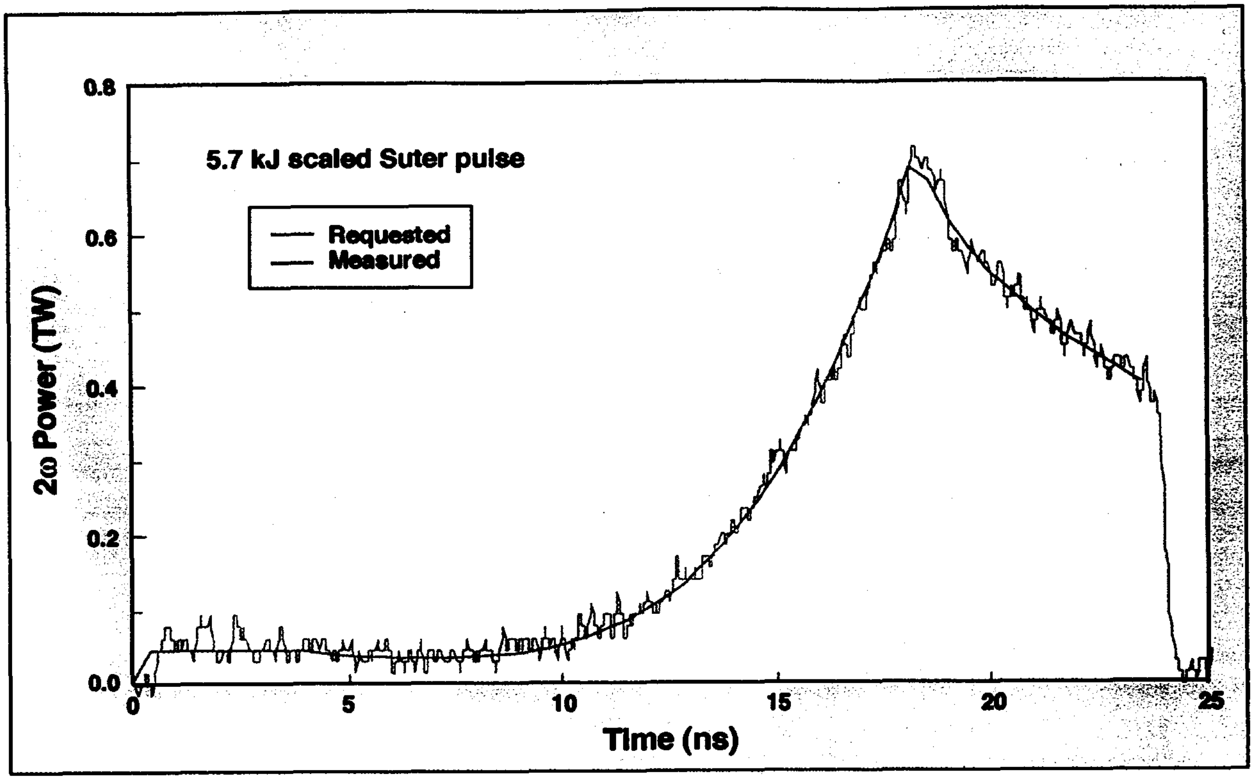

Fig. 7 An example of a shaped 2ω pulse with total energy of 5.7 kJ and pulse length of approximately 25 ns.

Additional laser performance shots have verified beam-to-beam timing of better than 6 picoseconds demonstrating the ability to control the laser pulse to about 1 part in 150,000 through the total laser beam path.

Beam uniformity on NIF at 1ω is required to be 10% or better. In order to achieve the required uniformity special compensation is used in the Injection Laser System Preamplifiers. Compensation corrects the non-uniform gain profiles in the large glass amplifier system by the application of spatial shaping in the pre-amplifier module. A combination of serrated apertures and patterned gain compensation masks are used. 1ω far-field divergence is measured to be smaller than 80% energy contained within 18 μradians required for NIF.

Temporal shaping is an important capability on NIF for meeting experimental needs. Figure 7 shows an example of a shaped 2ω pulse with total energy of 5.7 kJ and pulse length of approximately 25 ns. The measured pulse shape is overlaid on top of the requested shape showing NIF's capability for delivering prescribed pulse shaping. This particular pulse is of interest for ignition experiments to be conducted when NIF is completed.

Frequency conversion efficiency is important for maximizing the energy available for experiments. We have conducted studies to measure the conversion efficiency of the KDP doubler and deuterated KDP tripler crystals in the final optics system. Figures 8a and 8b show data and simulations for 2ω conversion efficiency measured on the PDS. The data shows that 2ω and 3ω conversion efficiency can provide >2 MJ full NIF equivalent energy.

IV. Conclusions and Future Directions

Completion of all 192 laser beams is scheduled for September 2008. During this time approximately 1500 experiments are planned in support of the Stockpile Stewardship Program, inertial confinement fusion, high energy density physics, inertial fusion energy, and basic science [9]. After project completion, NIF is expected to provide approximately 700 shots per year for a wide variety of experimental users as a national user facility.

In addition, we have begun looking at the design and deployment of high energy petawatt (HEPW) beam lines on NIF for high-energy-density science applications. We are studying a phased deployment starting with a kilojoule-class single beamline to be fielded in FY06 with a final capability for as many as 4 quads of additional HEPW beamlines [10].

The first physics experiments are already being performed on NIF and have been reported at a recent inertial fusion conference [11]. Initial experiments are studying laser-plasma interactions and hydrodynamics of shocked materials. In the coming year this unique facility will already be providing the first glimpses of conditions heretofore only found in the most extreme environments. This will be done under repeatable and well-characterized laboratory conditions for the benefit of basic and applied science [12].

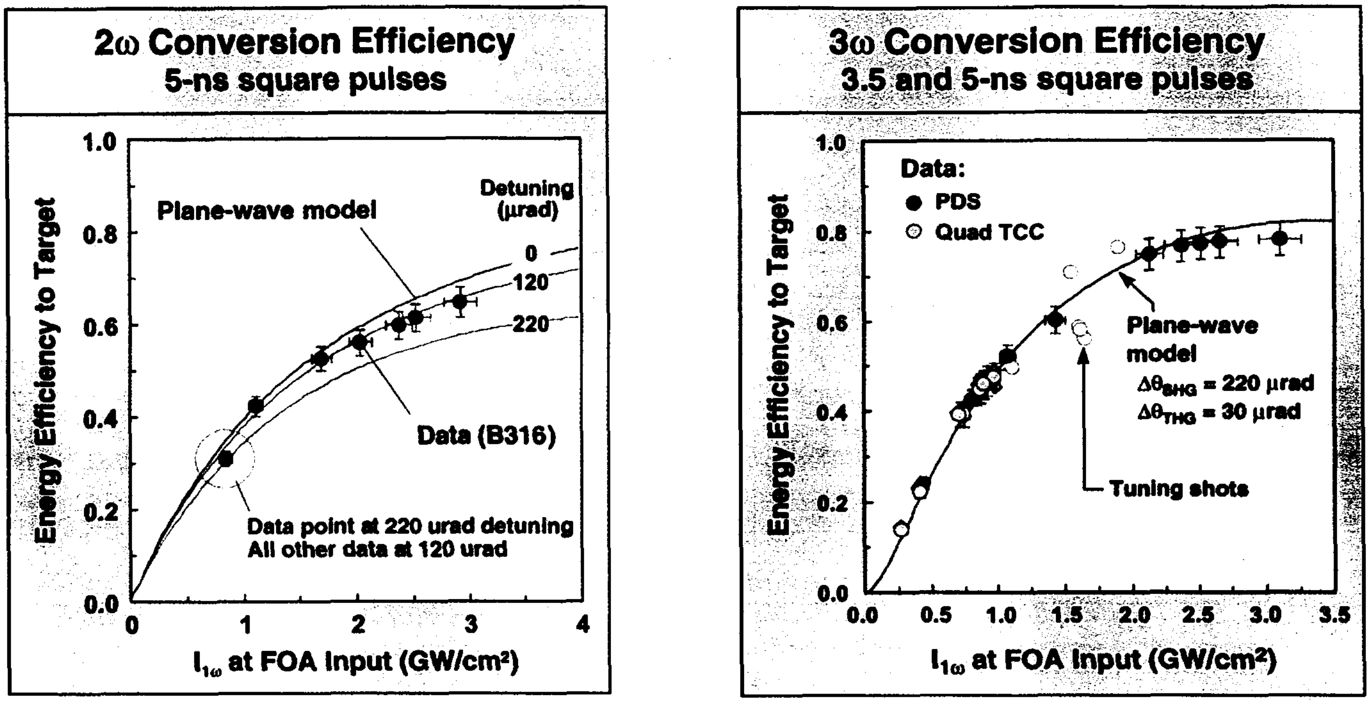

Fig. 8a on the left and 8b on the right shows measured 2ω and 3ω conversion efficiency, respectively, for a number of input powers. Overlaid on the data points is a plane-wave model that compares well with the measurements.

ACKNOWLEDGMENTS

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REFERENCES

[1] J. Lindl, *Inertial Confinement Fusion: The Quest for Ignition and Energy Gain Using Indirect Drive*, Springer-Verlag, 1998.

[2] *"Laboratory Microfusion Capability Phase-II Study,"* prepared by Interscience, Inc. for the Inertial Fusion Division Office of Research and Advanced Technology, ISI-TM9005281, May 31, 1990.

[3] *"Solid State Lasers for Application to Inertial Confinement Fusion (ICF),"* W. F. Krupke, ed., Proc. SPIE 2633, 1995.

[4] C. B. Tarter, "Inertial Fusion and Higher Energy Density Science in the United States," Proc. 2001 Conf. Inertial Fusion Sciences and Applications (IFSA 2001), K. A. Tanaka, D. D. Meyerhofer, J. Meyer-ter-Vehn, eds., Elsevier, 2002.

[5] E. Moses, et al., "The National Ignition Facility: Status and Plans for Laser Fusion and High-Energy-Density Experimental Studies," Fusion Science and Technology, V. 43, p. 420, May 2003.

[6] M. A. Newton, et al., "Initial Activation and Operation of the Power Conditioning System for the National Ignition Facility," Proceedings of the International Pulsed Power Conference 2003, Dallas, TX, June 15-18, 2003.

[7] E. Moses, et al., "The National Ignition Facility: The World's Largest Optics and Laser System," UCRL-151593-JC, submitted for publication in the SPIE Proc. Photonics West, January 2003.

[8] C. J. Stolz, et al., "Fabrication of meter-scale laser resistant mirrors for the National Ignition Facility, a fusion laser," submitted to the SPIE Proceedings of the International Symposium on Optical Science and Technology, Advances in Mirror Technology for X-ray, EUV Lithography, Laser, and Other Applications, 2003.

[9] G. Miller, "The National Ignition Facility: Experimental Capability," presented at the Third International Conference on Inertial Fusion Sciences and Applications (IFSA 2003), Monterey, CA, September (2003).

[10] C. Barty, et al., "Technical Challenges and Motivations for High Energy Petawatt Lasers on NIF," presented at the Third International Conference on Inertial Fusion Sciences and Applications (IFSA 2003), Monterey, CA, September 2003.

[11] S. Glenzer, et al., "Progress in Long Scale Length Laser Plasma Interactions," presented at the Third International Conference on Inertial Fusion Sciences and Applications (IFSA 2003), Monterey, CA, September 2003.

[12] For more information on the NIF Project please visit our web site at http://www.llnl.gov/nif